Simulation and Verification of Pulse Doppler Radar Systems

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Agilent Technologies

Agenda

- – Radar System Design Challenges
- – Signal Processing Algorithm Creation
- – Examples
  - Pulsed Doppler (PD) Radar
- – Wrap up

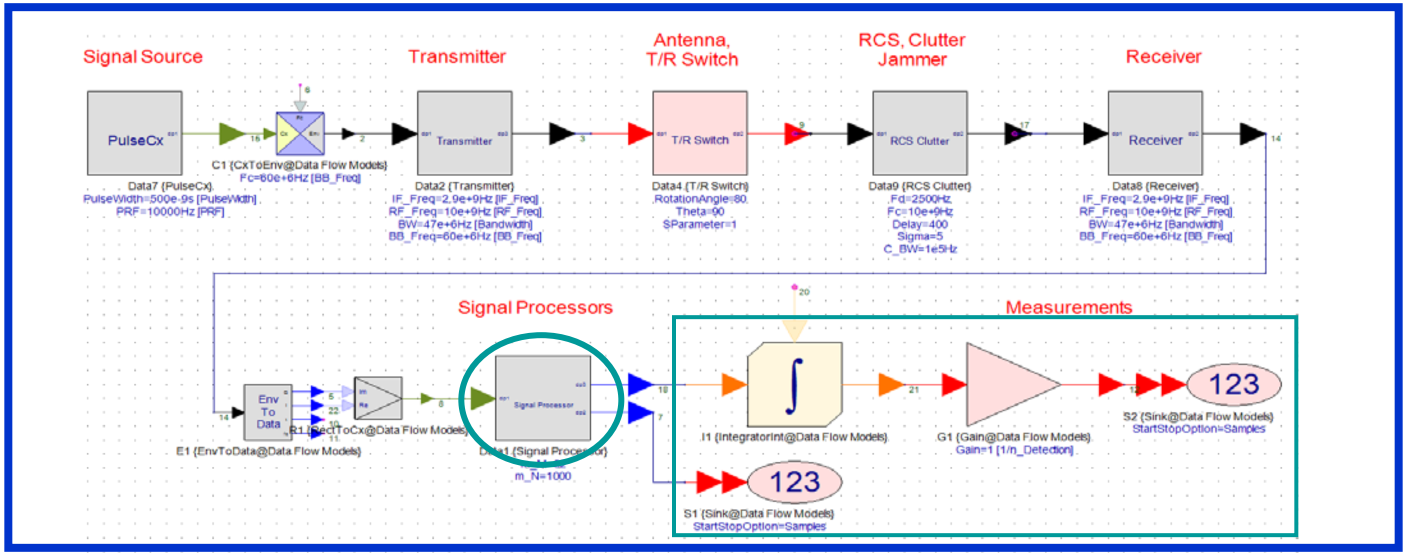
System Design Challenges

- Advanced radar systems are very complex
- It is based on radar signal processing algorithms
- Algorithm creation requires a platform for simulation and verification
- Enough models for signal generation, transmission, antenna, T/R switching, clutter, noise, jamming, receiving, signal processing and measurements are needed to create the advanced algorithm

Signal Processing Algorithm Creation

- System Platform is needed for both design and verification
- The Platform can provide
  - Algorithm design/verification environment for signal generation and performance measurements
  - User-friendly algorithm modeling & debug environment supporting variety of languages such as C++, Math Lang
  - Interface to test equipment to verify the implemented hardware (compared to the original pure algorithm)
    - Test sources include radar signal generation with RCS, Clutter, Jamming, Doppler frequency offset
    - Measurements include waveforms, spectra, detection rate, false alarm rate (FAR).

Platform for Simulation



Tx Waveform Library

- Radar Pulse Generator
- Coherent Signal Generator for Single or Multiple Channel

T/R Component Library

- DAC
- PA
- Up Converter
- Filter
- DDS
- LNA
- Down Converter
- ADC

Antenna Library

- Antenna Models
- T/R Antenna Array
- Antenna Propagation

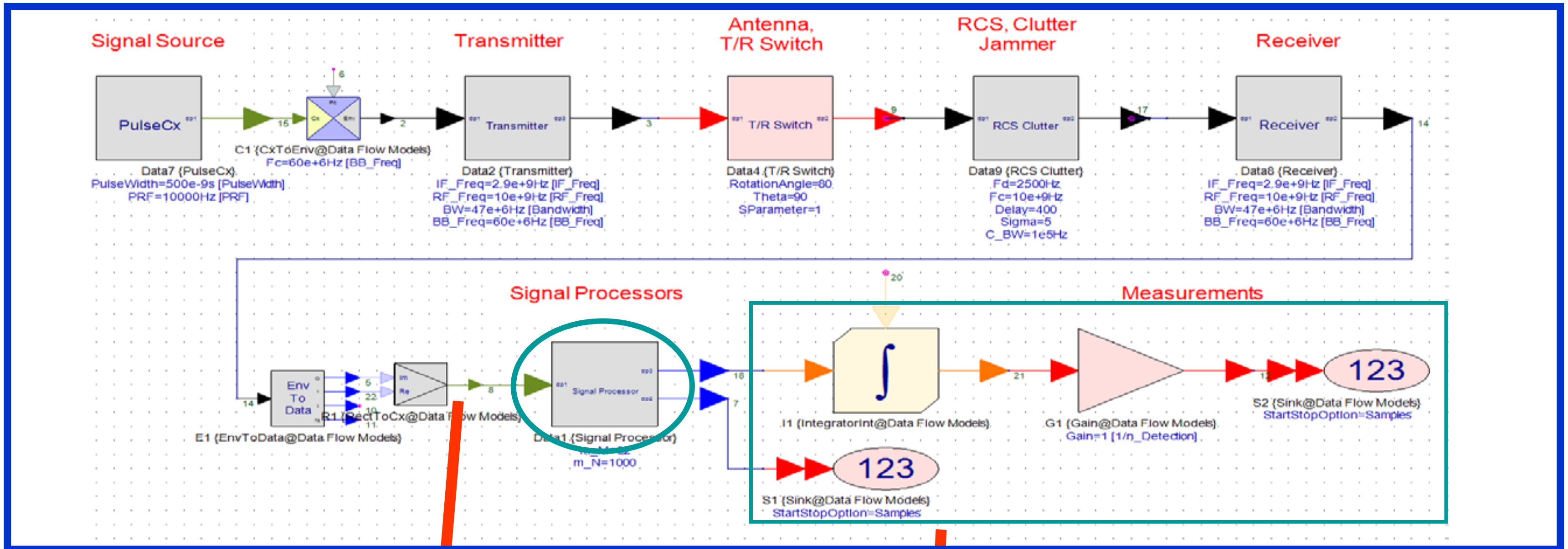
Radar Environment

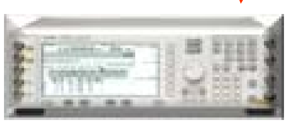
- Target
- Clutter
- Jammer
- Interference

Radar Signal Processing Library

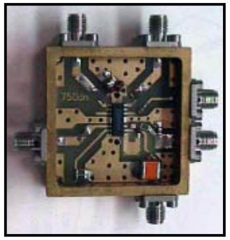
- Digital Pulse Compression
- Moving Target Indication (MTI)
- Moving Target Detection (MTD)
- Constant False Alarm Rate (CFAR)
- Digital Beamformer
- Space-Time Adaptive Processing (STAP)

Platform for Verification

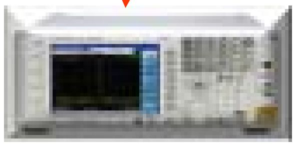




ESG/PSG/MXG

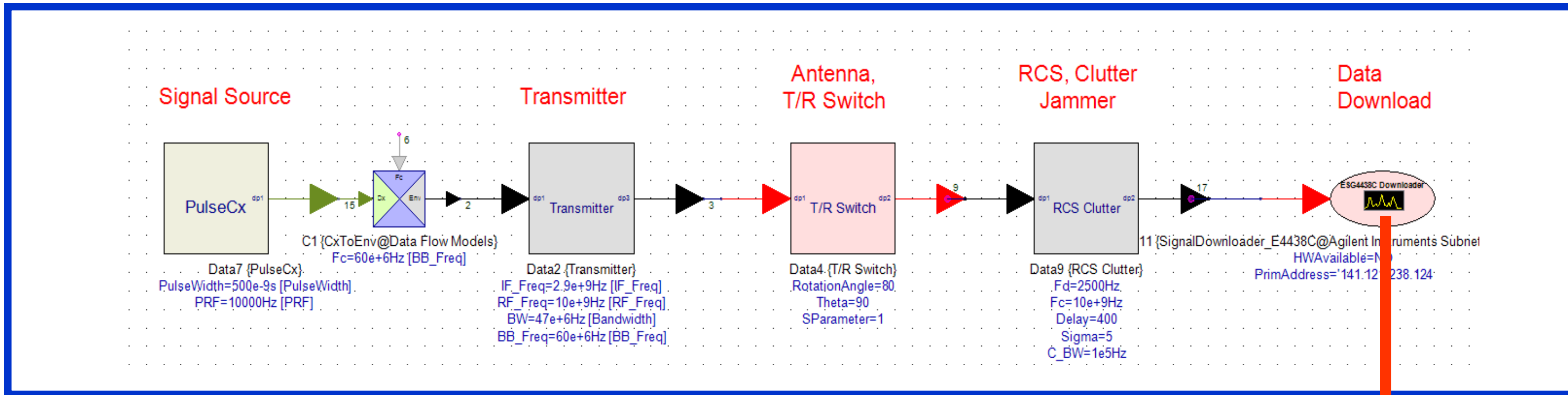


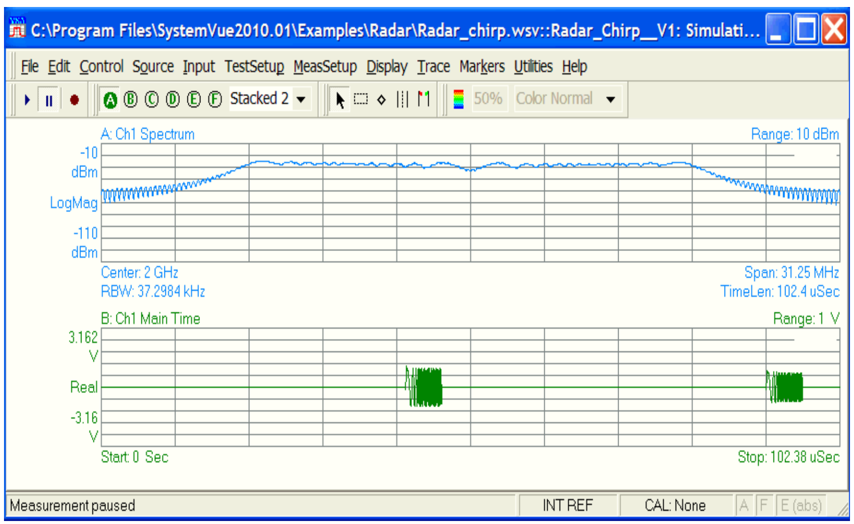
Signal Processor
Hardware

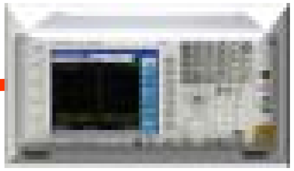


PSA/MXA/VSA
LA, Scope

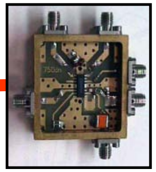
Platform - Generate Test Signals



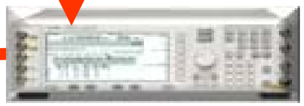




Signal Analyzers
Logic Analyzers,
Scopes

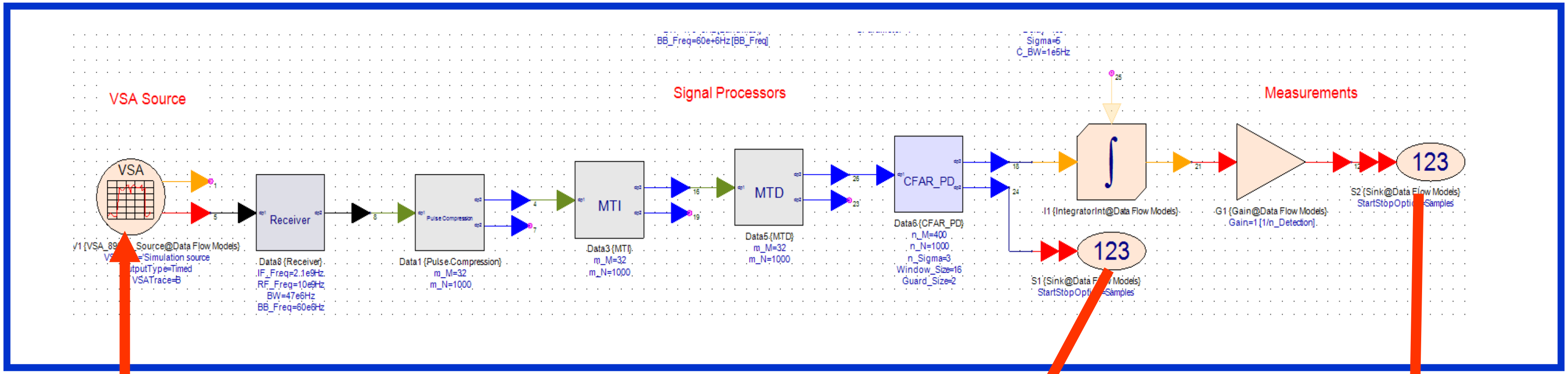


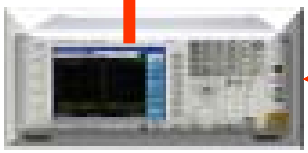
Signal Processor
Hardware



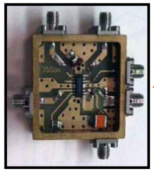
Signal Generators

Platform - Expand Measurements



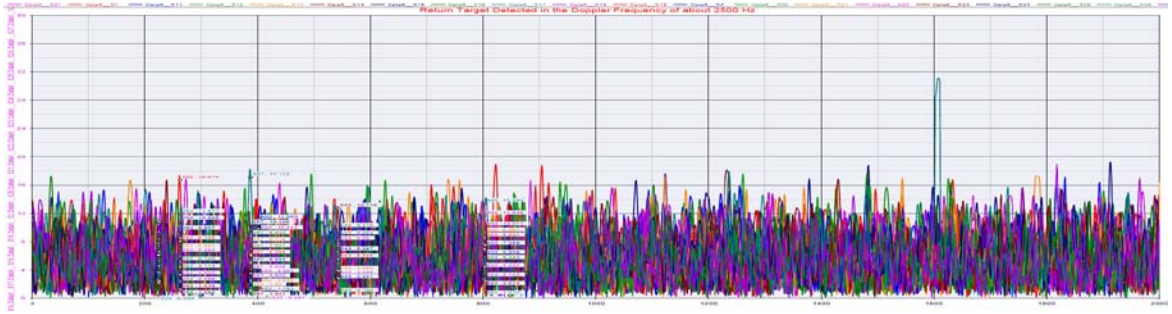


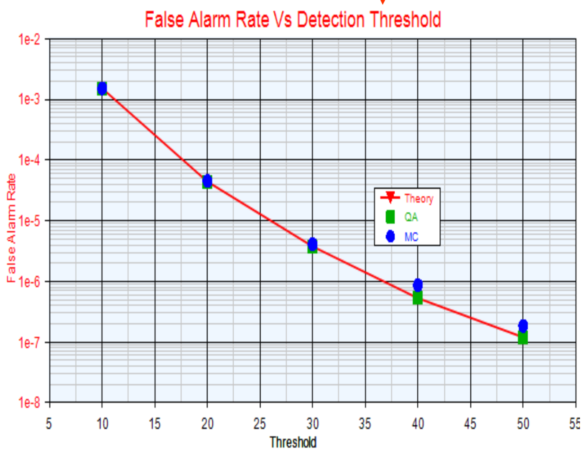
PSA/MXA/VSA
LA, Scope



Signal Processor
Hardware

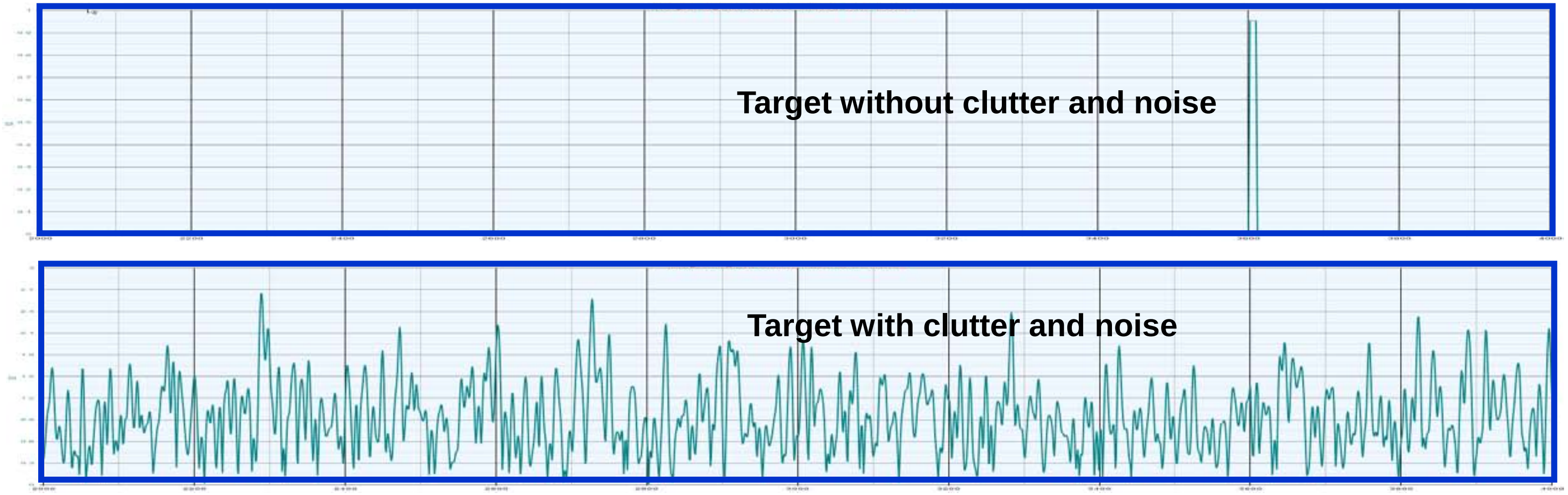
ESG/PSG/MXG





Pulsed Doppler Radar System

- PD radars are extremely valuable for finding small moving targets hidden by heavily cluttered environments
- Unlike the continuous waveform (CW) radar, the PD radar has ability to detect angle, distance, *and also velocity*
- Typical examples: low-flying aircraft and anti-ship missiles, weather
- PD radars are used for many military and commercial applications



PD Radar System – In Principle

- The Radar Transmission signal and Returned signal [1,2] are given by

$$S(t) = A(t)Cos(2\pi f_c t)$$

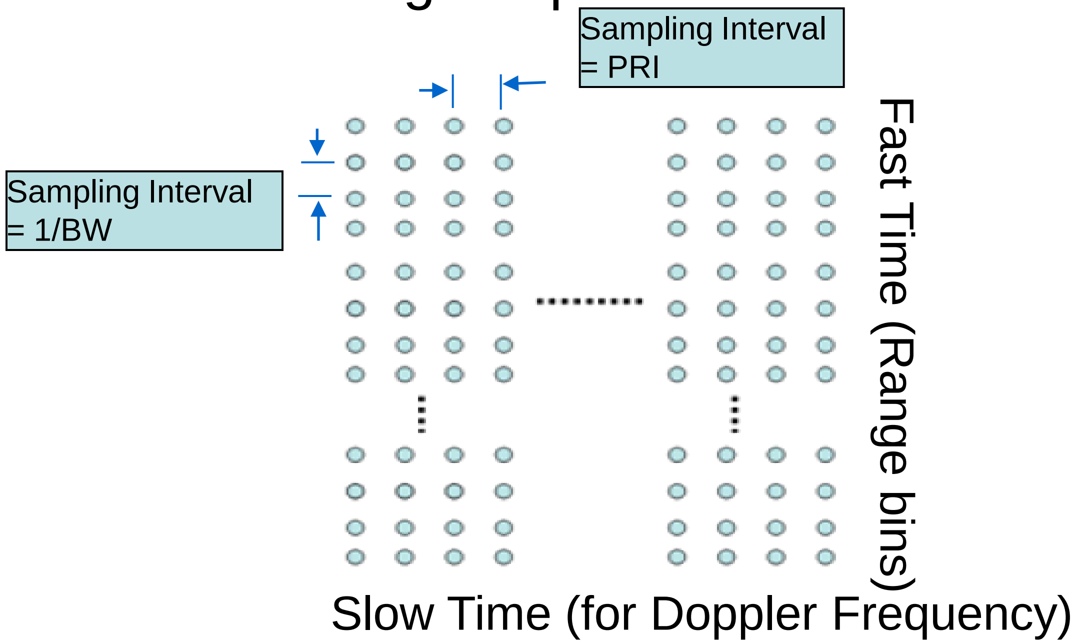
$$S(t-\tau) = A(t)Cos(2\pi(f_c + f_d)t - \tau) + N_C(t) + N_n(t) + N_j(t)$$

- Cannot detect the target in time domain because small moving targets are hidden by heavily cluttered environments
- Must detect the signal in frequency domain using the Doppler frequency analysis
- We must collect return data and process in both range and frequency domain for estimating $\hat{\tau}$ and $\hat{f}_d$.
- 2-dimensional signal processing is required for moving target indicator (MTI) and moving target detection (MTD).
- Constant false alarm rate (CFAR) processing is needed for auto-detection in PD process. Without CFAR, auto-detection will fail.

PD Radar System – In Principle

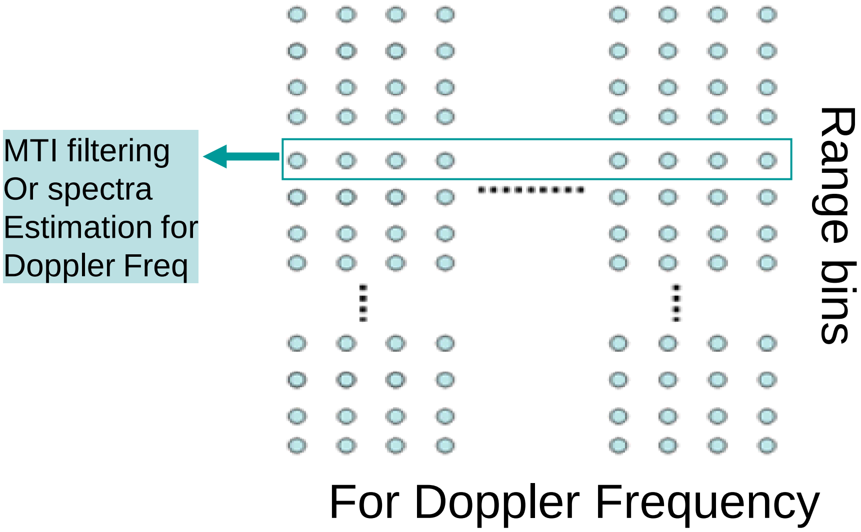
2-D data matrix of coherent, baseband returns for *M pulses*

- Fast time sample rate is 10^5 to 10^8 samples/sec
- Slow time sample rate is the PRF, 10^3 to 10^5 samples/sec
- Collected using the pulse burst waveform



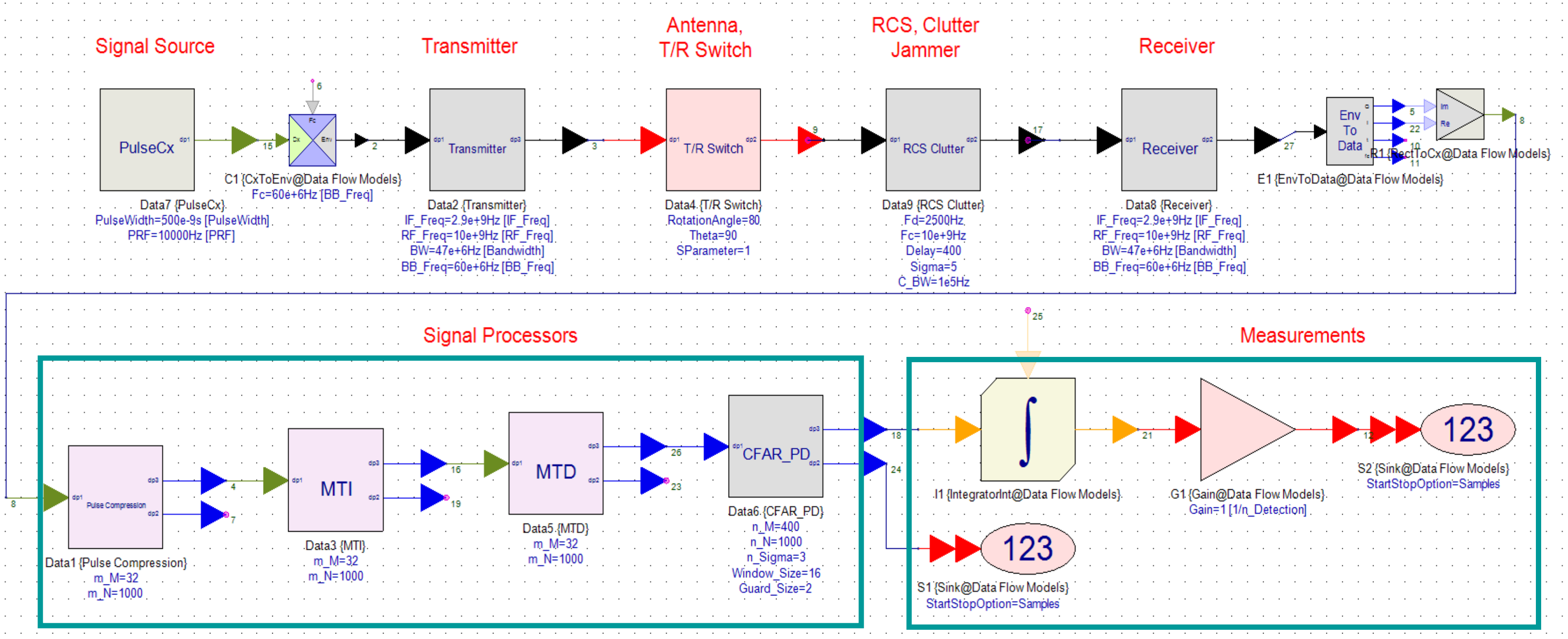
PD Radar System – In Principle

- To extract the Doppler frequency and the target delay 2D signal processing is needed
  - Doppler processing operates on each row of this Matrix
    Two major processing
    - MTI applies a linear filter to each row
    - PD applies a spectrum estimation to each row



PD Radar System Structure

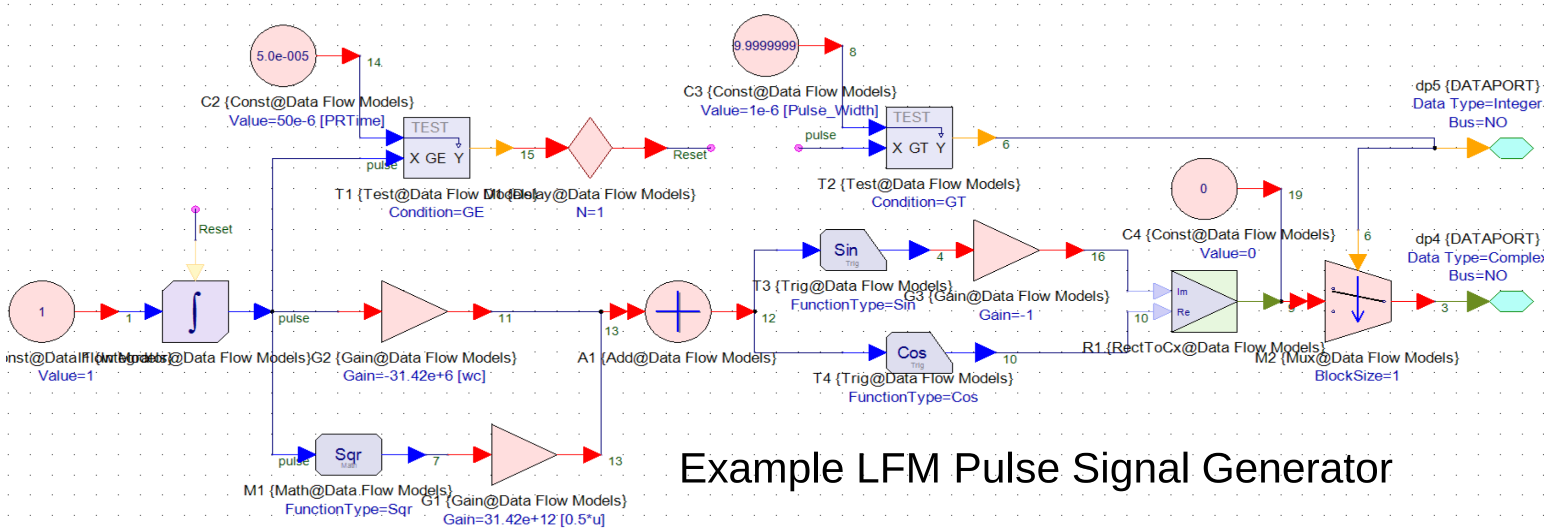
– For PD, based on the generic radar system structure (shown in slide 5), the signal processors include Pulse Compression, MTI, MTD and CFAR



PD Radar System – Signal Source Models

Signal sources include:

- Pulse signal generator
- Linear FM pulse signal generator
- Nonlinear FM signal generator
- Polyphase code generator



Example LFM Pulse Signal Generator

PD Radar System – Target Return Model

Target return model

- Including RCS, Doppler effect, Delay and Attenuation
- Fluctuant RCS types: Swirling 0, Ⅰ, Ⅱ, Ⅲ, Ⅳ linear FM pulse signal generator

$$s_r(t-t_r) = kA(t-t_r)\cos[2\pi(f_0 \mp f_d)t - 4\pi R_0/\lambda + \varphi]\cdot U(t-t_r)$$

Where R is the distance between radar and target, tr is the path delay, so tr=2R/c.
Because target has a velocity vr, so the distance K is the effects of the magnitude, including the RCS and distance attenuation.

PD Radar System – Clutter

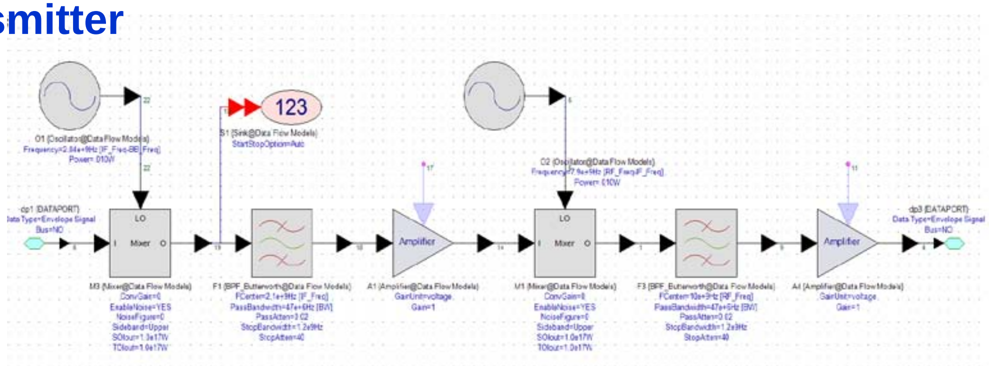
Choice of 4 amplitude probability distribution functions (PDF) and 3 power spectrum density (PSD) functions

- PDF
  - Rayleigh
  - Log-Normal
  - Weibull
  - K – Distribution
- PSD
  - Gaussian
  - Cauchy
  - All Pole

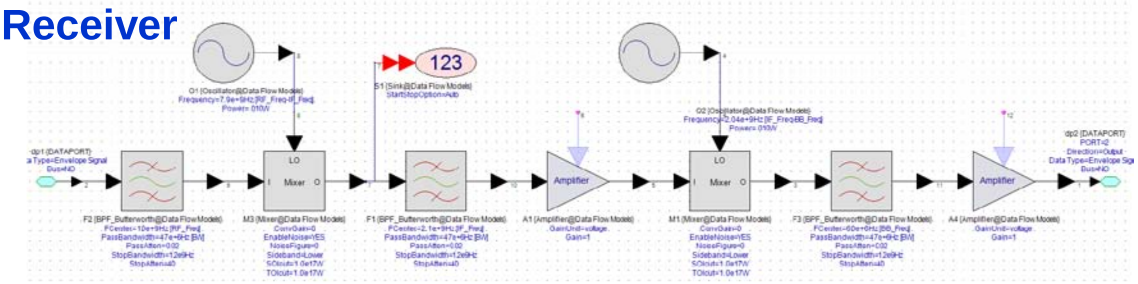
PD Radar System – Transmitter and Receiver

- The RF transmitter includes oscillators, modulator, amplifiers and filters
- The RF receiver includes oscillators, demodulator, amplifiers and filters

RF Transmitter

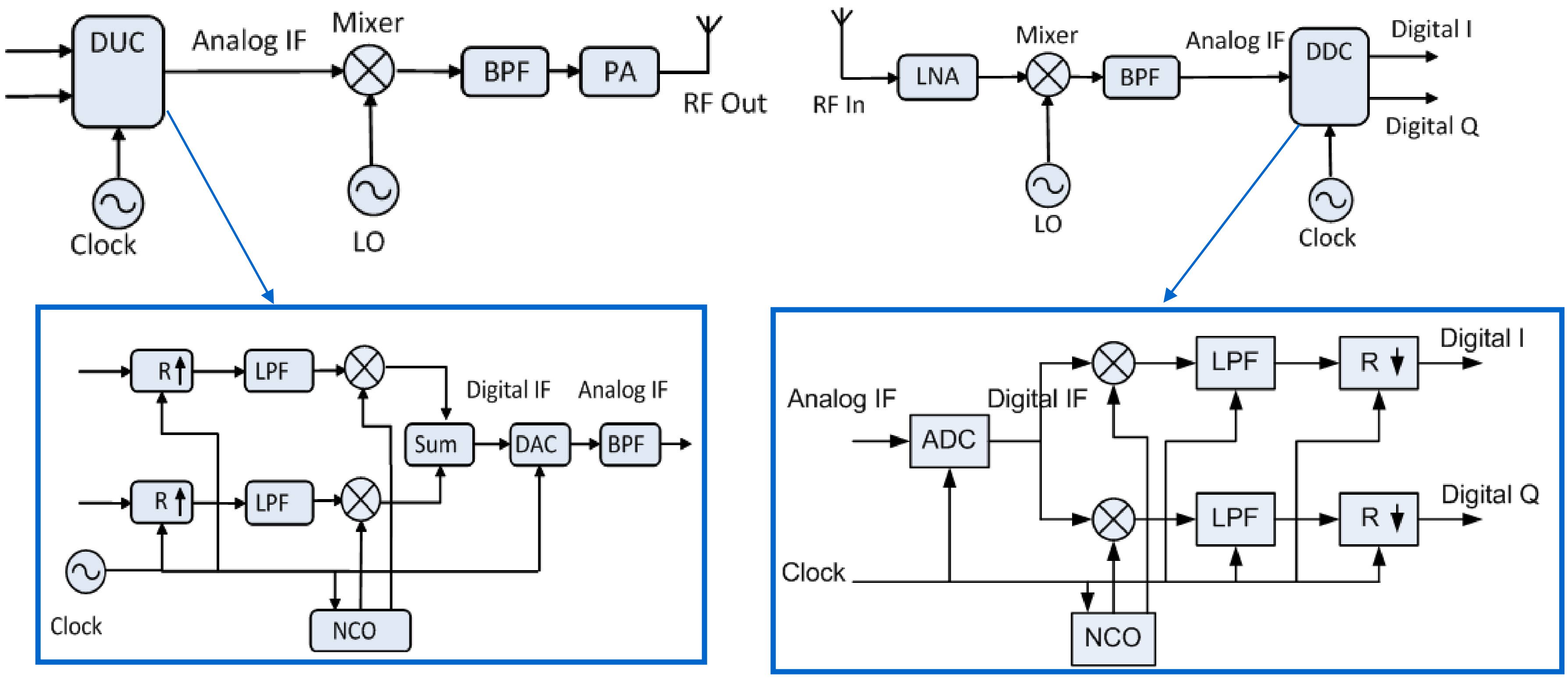


RF Receiver



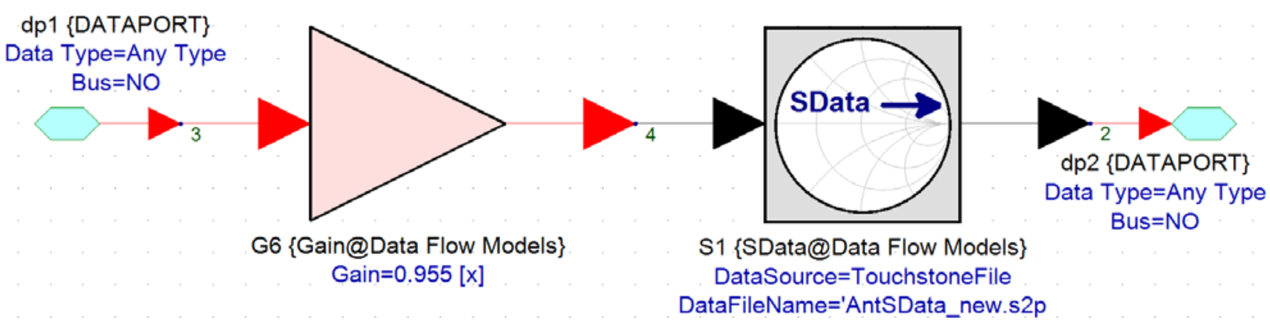
PD Radar System – Digital Up Converters

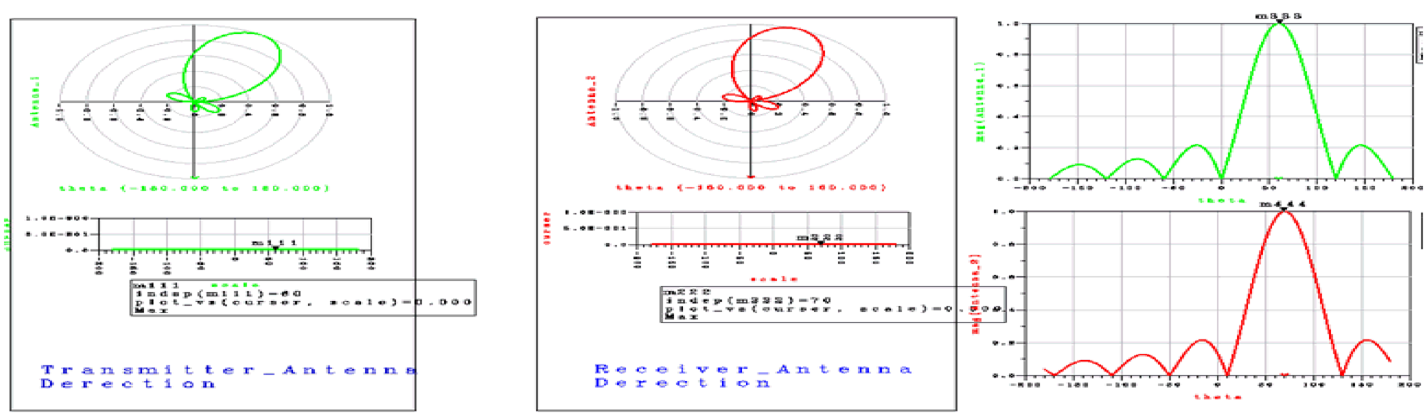
– Digital Up/Down converter (DUC/DDC) for digital IF



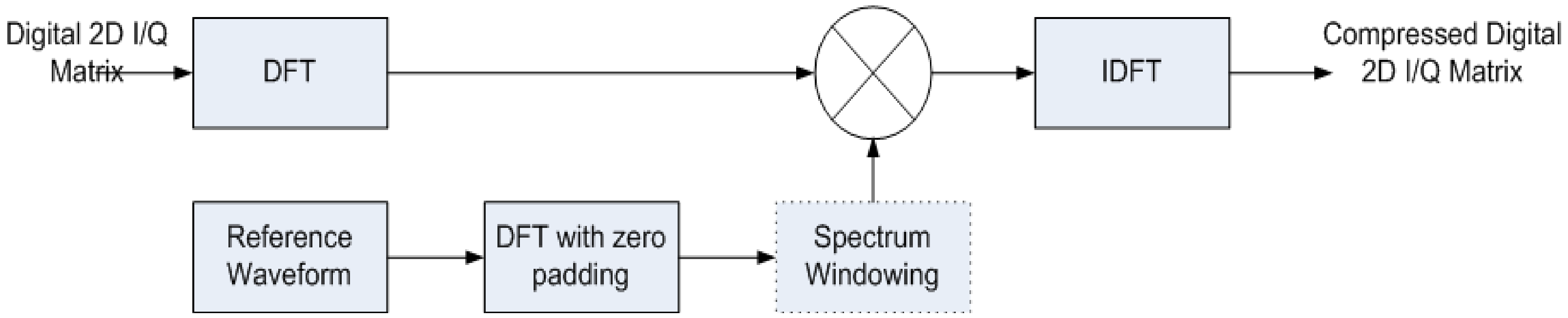
PD Radar System – Antenna

- S-Parameter based
- Antenna rotation pattern is considered
- Leverage EM simulation tools antenna analysis result





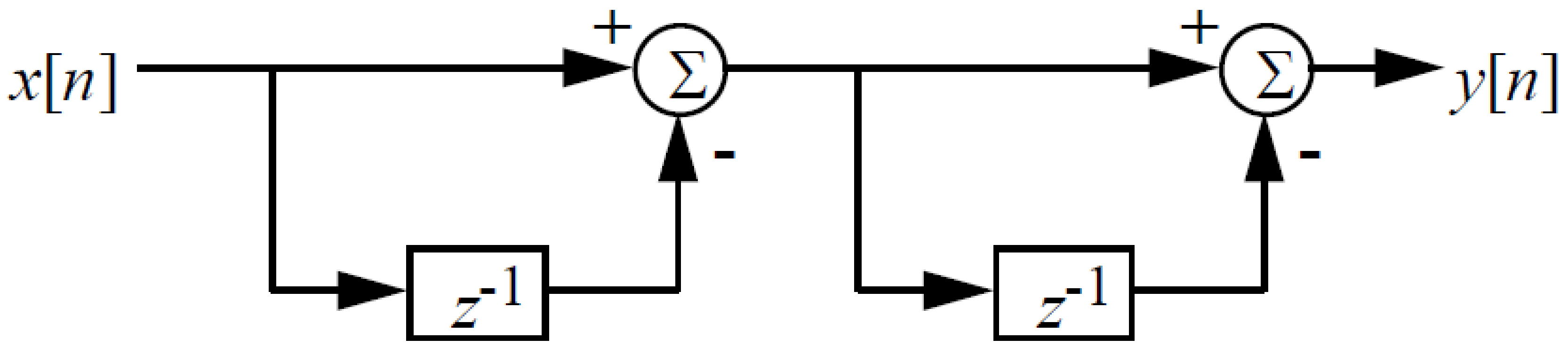
PD Radar System – Pulse Compression



PD Radar System – Moving Target Indicator

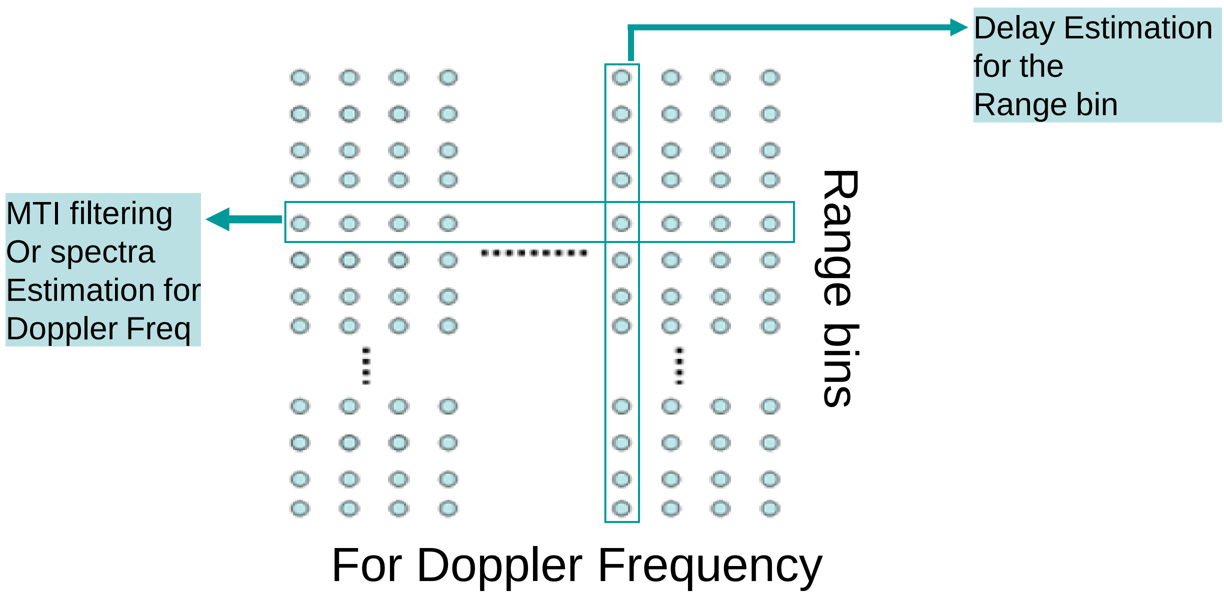
- The basic idea for the moving target indicator (MTI) is to filter the clutter at DC or very near DC but keep the other spectrum region remaining flat
- A three-pulse (double, second-order) canceller can be formed by cascading two first-order sections
- Transfer function

$$H(z) = 1 - 2z^{-1} + z^{-2}$$



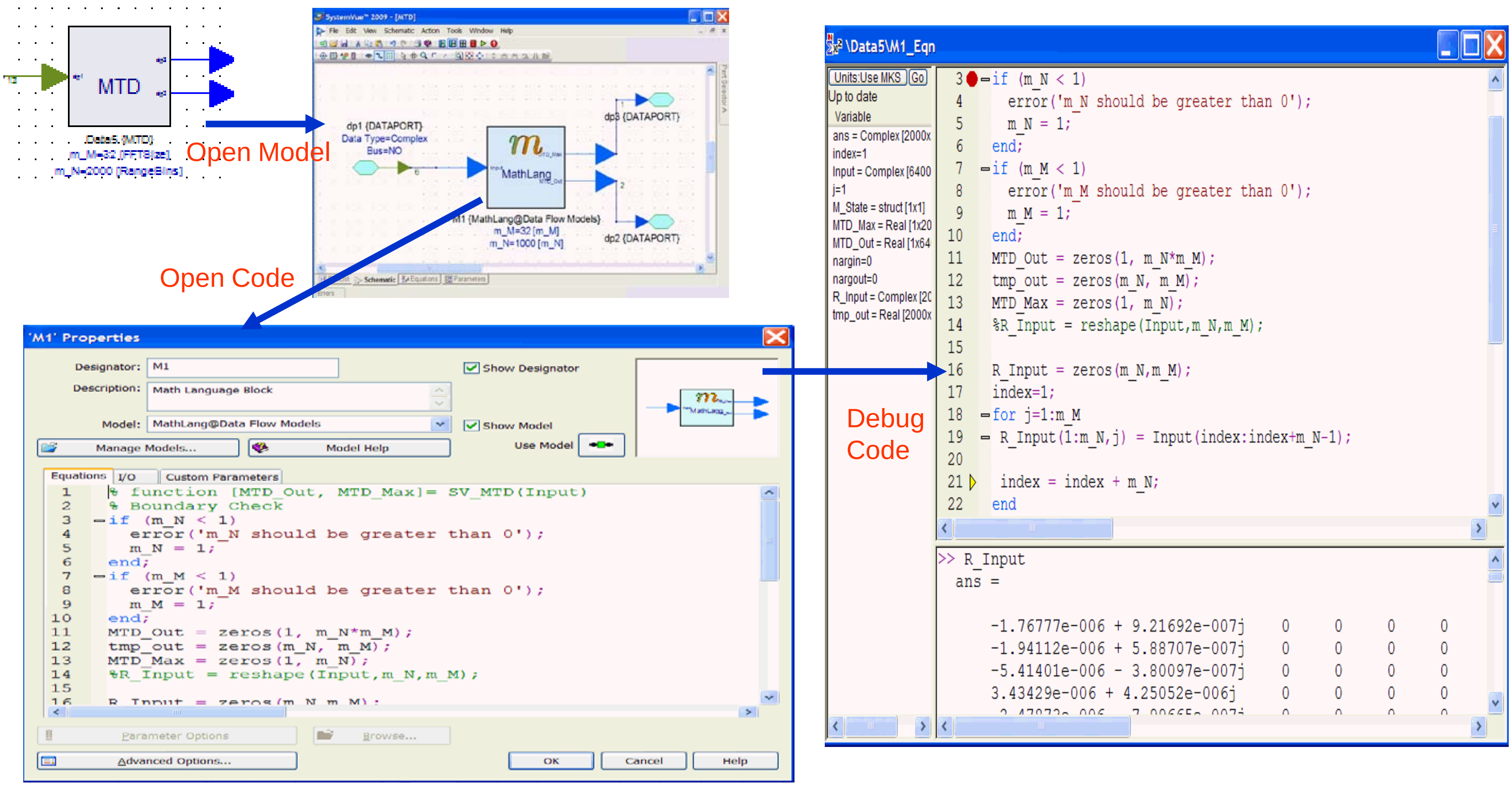
PD Radar System – Moving Target Detection

- A bank of Doppler filters or FFT operators cover all possible expected target Doppler shift.
- The input data is collected in a repetition period using a data bank. Then data points within the same range are correlated and processed using FFT until all data is processed in the data bank.



PD Radar System – MTD Model

– The MTD model created using Math Language

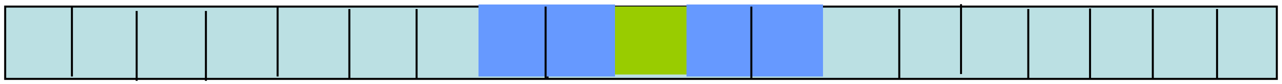


PD Radar System – CA CFAR

– **Test cell**: the detected cell

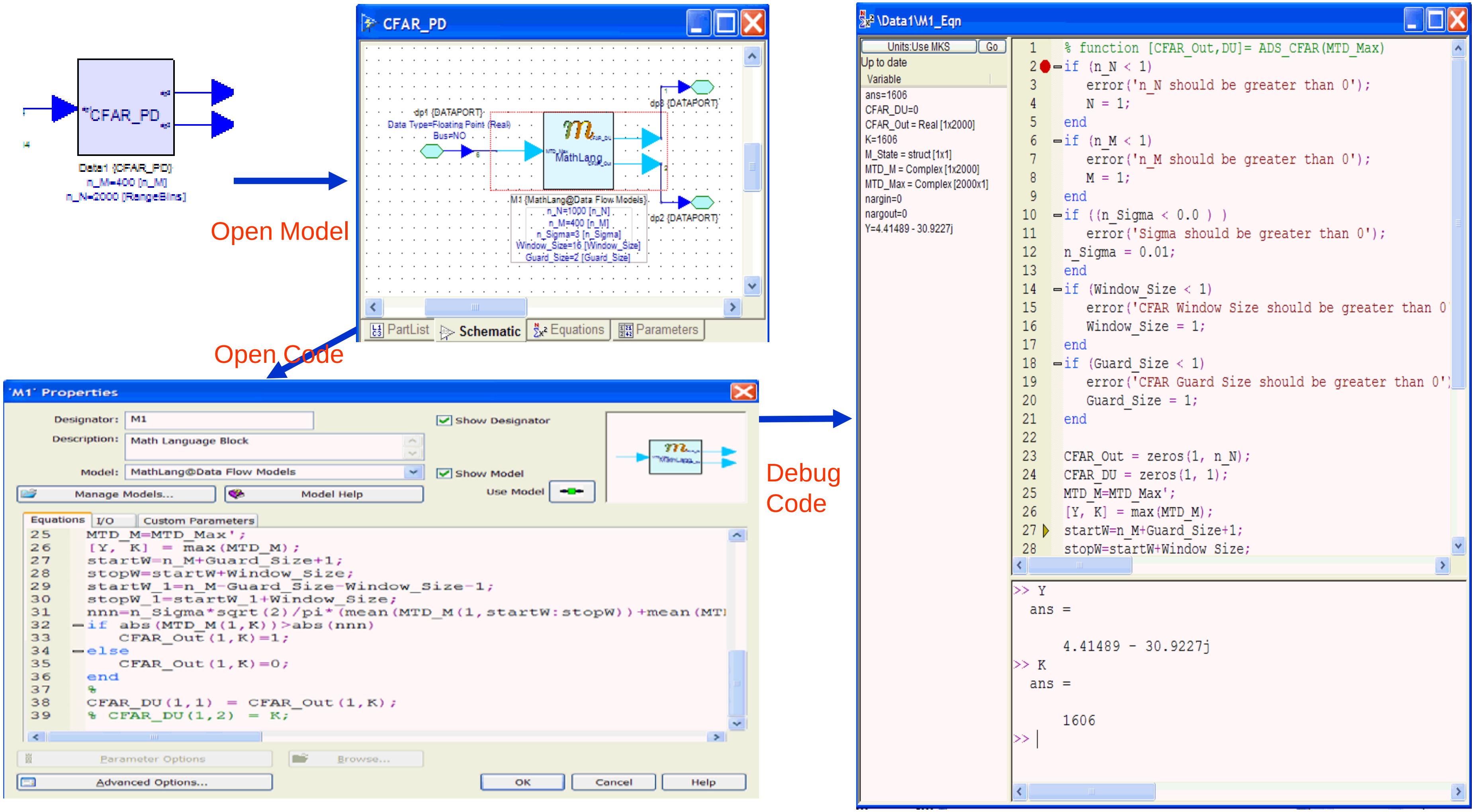
– **Guard or gap cell**: value not to be included in the interference estimate due to possible target contamination

– **Reference cell**: values assumed to be interference only, thus used to estimate interference parameters



PD Radar System – CFAR Model

– The CFAR model created using Math Language



PD Radar System – Measurements

- Basic measurements
  - Waveform
  - Spectrum
  - Signal Noise Ratio

- Advanced measurements
  - Estimation of Distances and Speed
  - Detection probability

  Pd = Number of Successful detection / Total number of Tests
  - False Alarm probability

  Pf = Number of False Error / Total Number of Tests

  Importance sampling will be used to speed up the Pf simulation [3].

PD Radar System – Simulation Setup

– All key parameters can be set in the parameter table defined for the PD simulation system as seen as below. User can very easily edit, add or delete any parameter.

PD_Radar

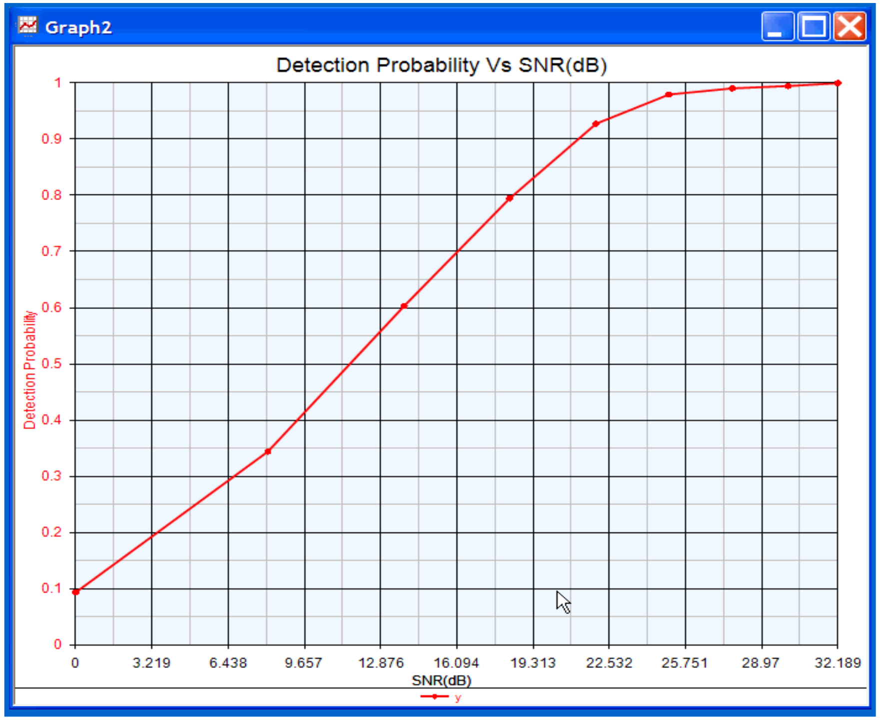
Name	Description	Default Value	Units	Tune	Show	Initially Use Default
PulseWidth	Pulse Width	500e-9	s	☐	☑	☐
PRF	Pulse Repeat Frequency	10000	Hz	☐	☑	☐
Fd	Doppler Frequncy	8125	Hz	☐	☑	☐
Range	Target Range	12000	M	☐	☑	☐
RF_Freq	RF Frequency	10e9	Hz	☐	☑	☐
IF_Freq	IF Frequency	2.9e9	Hz	☐	☑	☐
BB_Freq	Baseband Frequency	60e6	Hz	☐	☑	☐
Bandwidth	Band Width	47e6	Hz	☐	☑	☐
SamplingFreq	Simulation Sampling Frequency	20e6	Hz	☐	☑	☐
FFTSize	FFT Size	32	( )	☐	☑	☐
n_M	Detection Cell	400	( )	☐	☑	☐
Window_Size	CFAR Window Size	32	( )	☐	☑	☐
Guard_Size	CFAR Guard Size	6	( )	☐	☑	☐
Sigma	Clutter Standard Diviation	2.5	( )	☐	☑	☐
C_BW	Clutter Bandwidth	1e6	Hz	☐	☑	☐
RotationAngle	Antenna Rotation Angle	60	deg	☐	☑	☐
Theta	Antenna Angle	90	deg	☐	☑	☐
n_Sigma	Noise Standard Diviation	3	( )	☐	☑	☐
n_Detection	Number of statistics for the detec	1	( )	☐	☑	☐

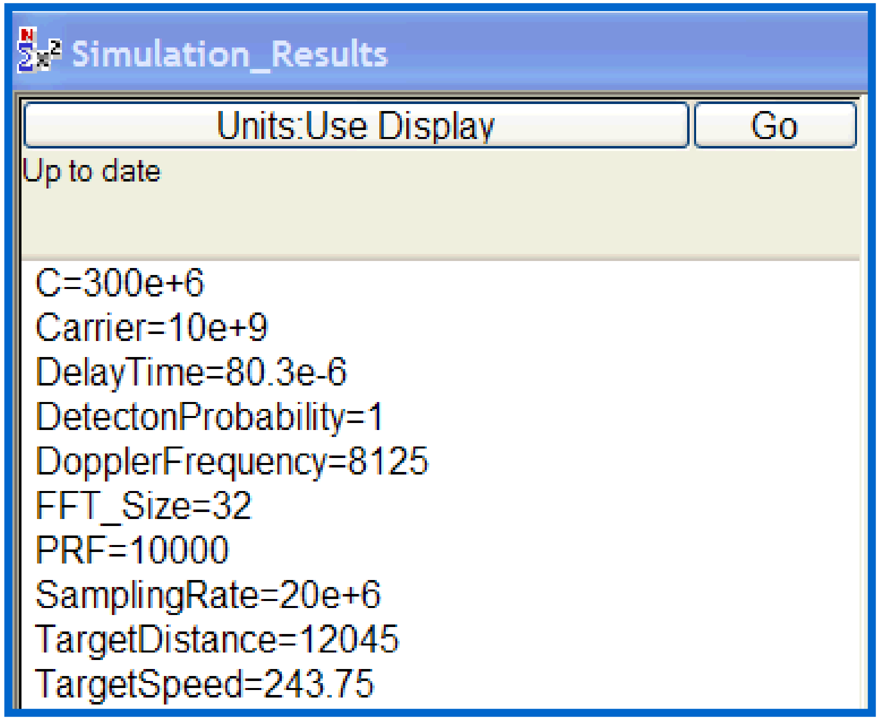
PD Radar System – Simulation Results

– PD radar extremely valuable in situations involving small moving targets hidden by heavily cluttered environments

PD Radar System – Performance

– Detection Probability
– Estimation of Target Distance and Speed





Summary

- Algorithms are critical for high-performing advanced radars
- A unified approach using Agilent SystemVue was demonstrated
  - Provides a user friendly environment for algorithm development
  - Integrates software and hardware to verify algorithms
- A development example for PD radar key algorithms was shown
- SystemVue can also be used to develop algorithms for Digital Array Radar plus Space-time adaptive processing (STAP) and MIMO Radar

References

1. I. Skolnik, Radar Handbook, 2nd ed. McGraw-Hill,Inc. 1990
2. D. Curtis Schleher, MTI and Pulse Doppler Radar, Artech House, Inc. 1991
3. Dingqing Lu and Kong Yao "Importance Sampling Simulation Techniques Applied to Estimating False Alarm Probabilities,"

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